Photometric Analysis of the Apollo Landing Sites using Lunar Reconnaissance Orbiter NAC Images

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Motivation

- The effects of the Apollo (and Surveyor and Luna) descent engine plumes are visible as photometric anomalies at the landing sites.

- Questions:
  - What are the effects in terms of exhaust plume erosion?
  - How big are the affected blast zones (BZs)?
  - What are the reflectance variations between the BZ and background?
  - How do these variations relate to changes in grain size, small-scale topography, soil maturity, soil composition, etc.?
  - How do the Apollo BZs compare to those of Surveyor and Luna?

- Apply knowledge to future manned and robotic missions to the Moon and other planetary bodies

LROC Landing Site Images

Apollo 11
image M129133239R
(*i*=62.61 °, *e*=9.39 °,
g=71.99°)

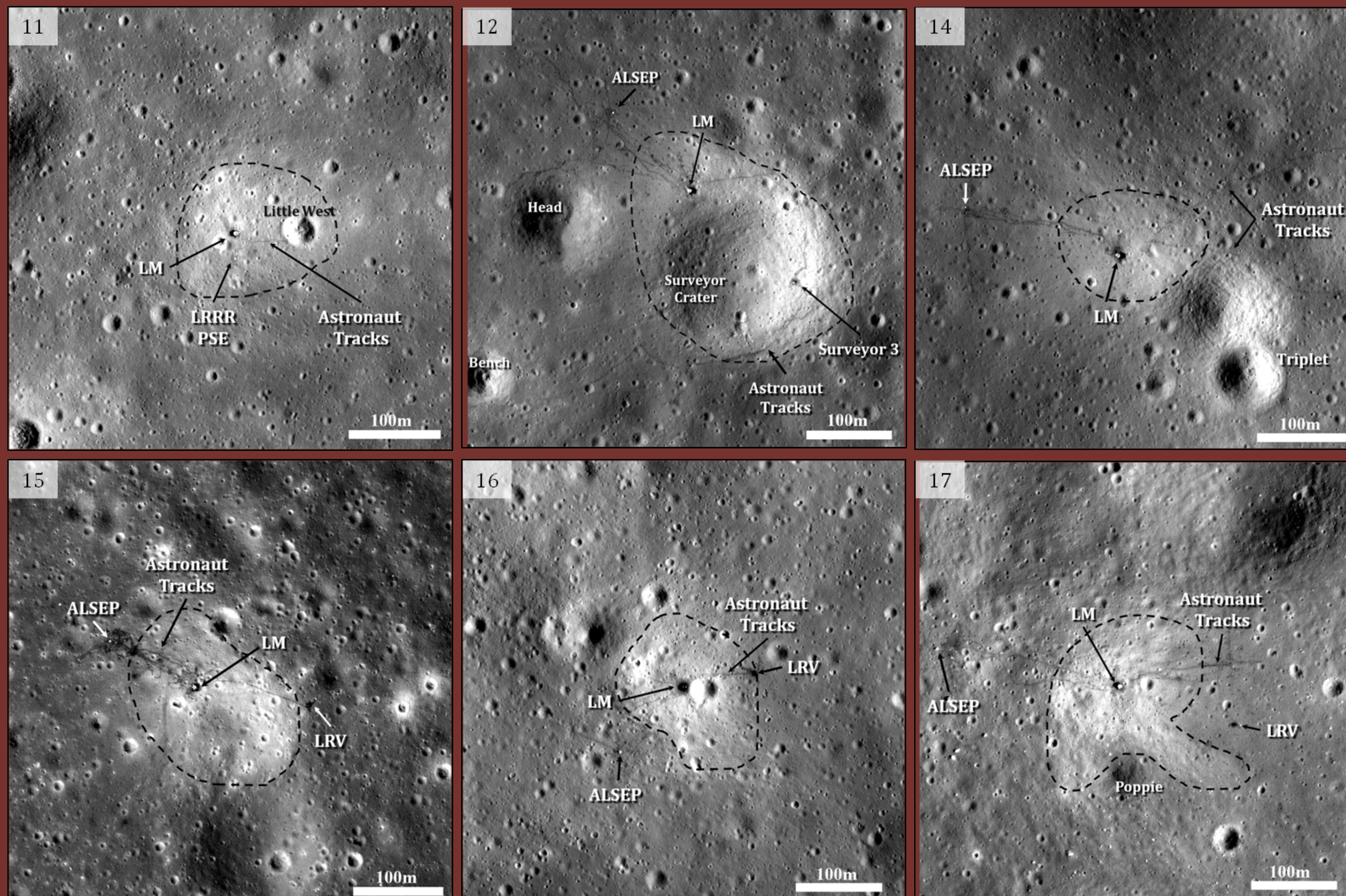
Apollo 12 and Surveyor 3
image M120005333L
(*i*=52.1 °, *e*=21.3°,
g=73.4°)

Apollo 14
image M150633128L
(*i*=59.9 °, *e*=17.2°,
g=77.1°)

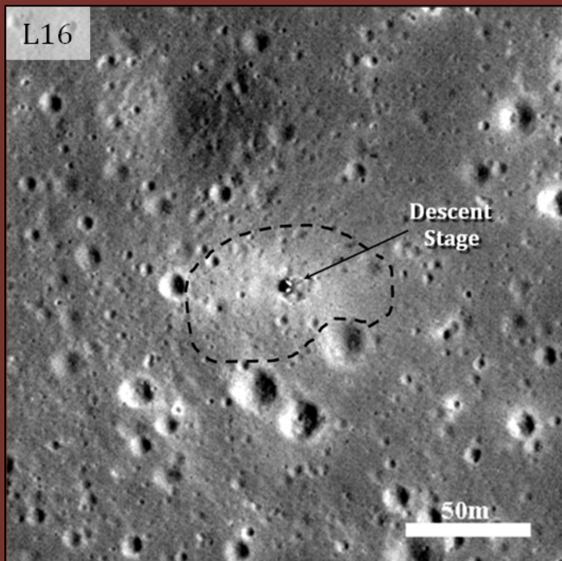
Apollo 15
image M122184104R
(*i*=35.1 °, *e*=8.8 °, *g*=42.1°)

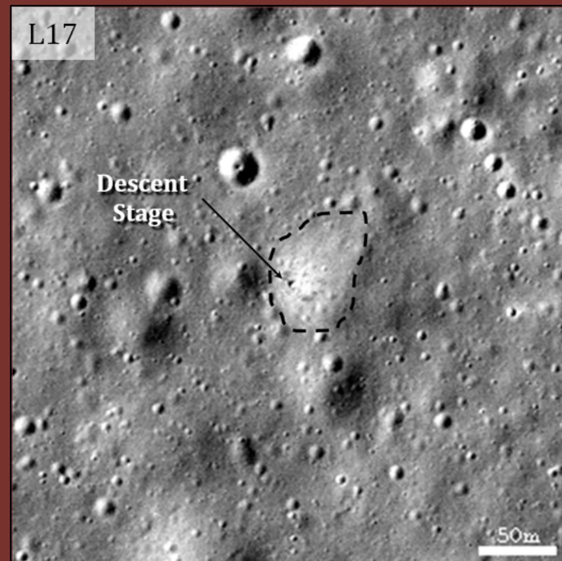
Apollo 16
image M113853974R
(*i*=54.7°, *e*=0.1 °, *g*=54.8°)

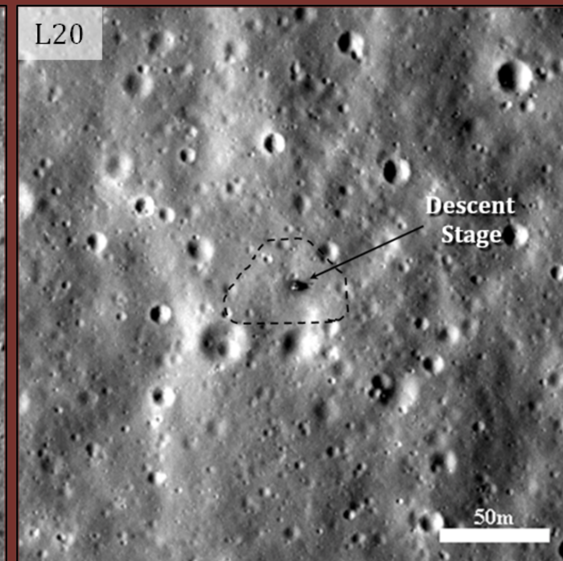
Apollo 17
image M113758461R
(*i*=55.7 °, *e*=14.9 °,
g=70.2°)

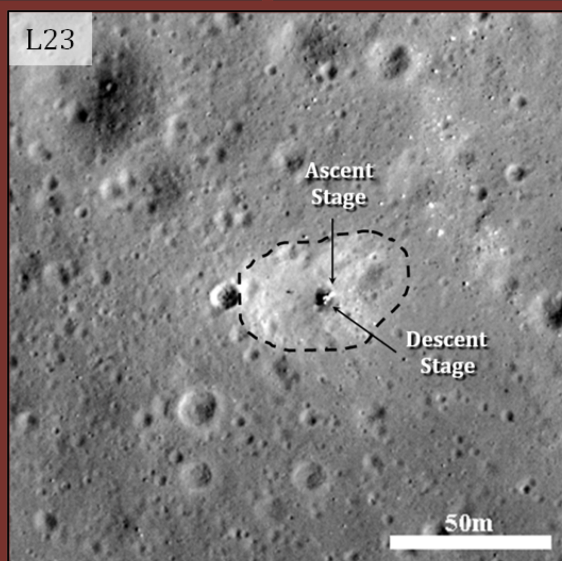


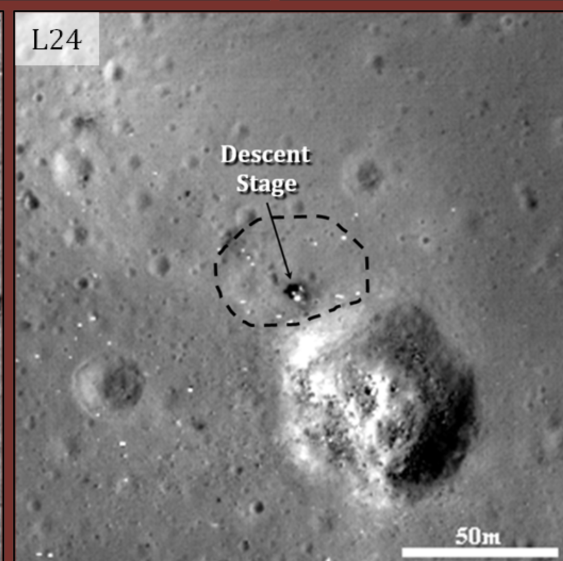
Luna Landing Sites











Luna 16
image M159582808L
(i=44.2°, e=0.9°, g=43.3°)

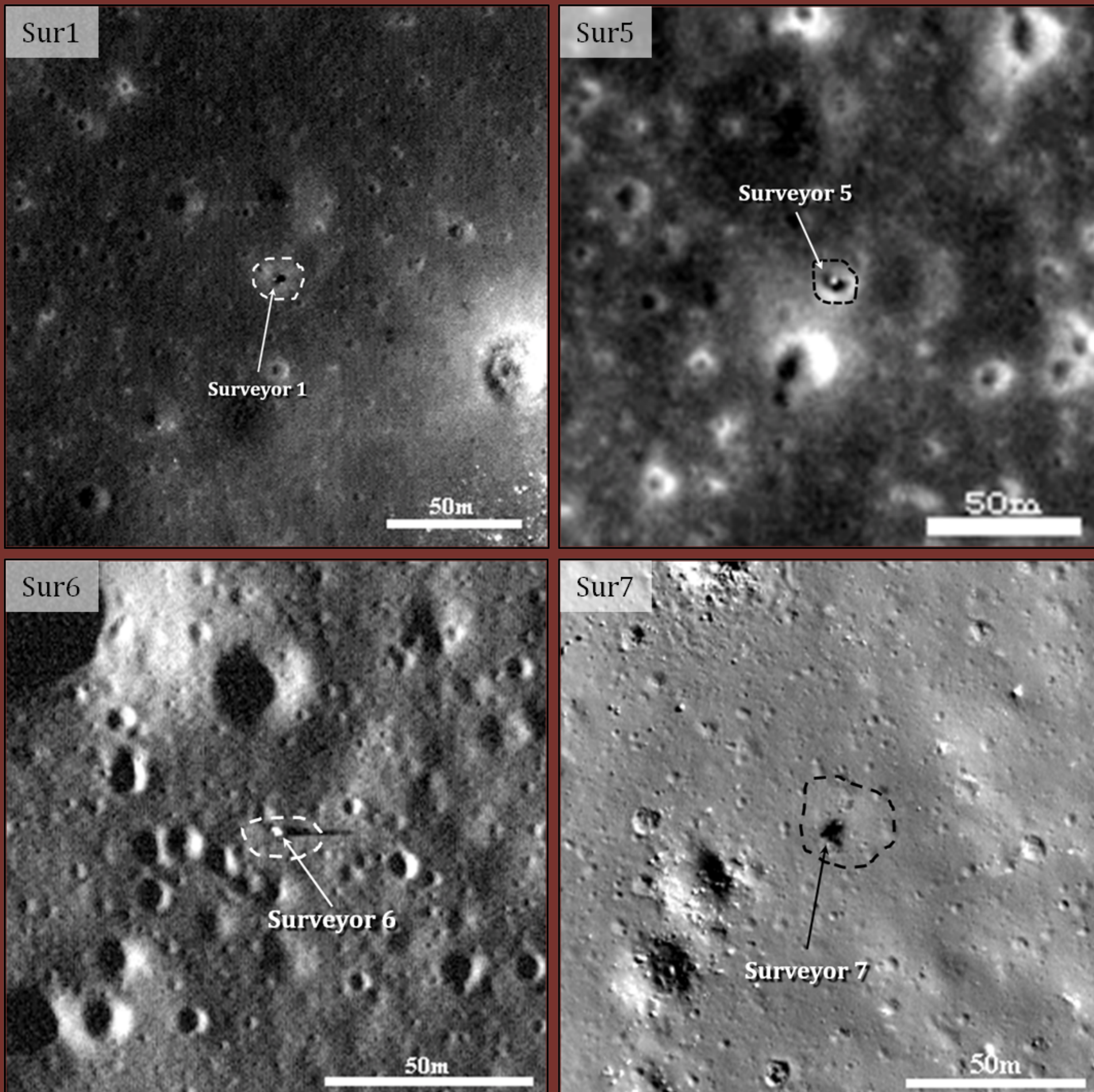
Luna 17
image M114185541R
(i=66.4°, e=1.2°, g=65.4°)

Luna 20
image M119482862R
(i=58.7°, e=3.9°, g=54.8°)

Luna 23
image M174868307R
(i=40.5°, e=20.9°, g=60.7°)

Luna 24
image M174868307L
(i=40.5°, e=23.8°, g=63.4°)

Surveyor Landing Sites



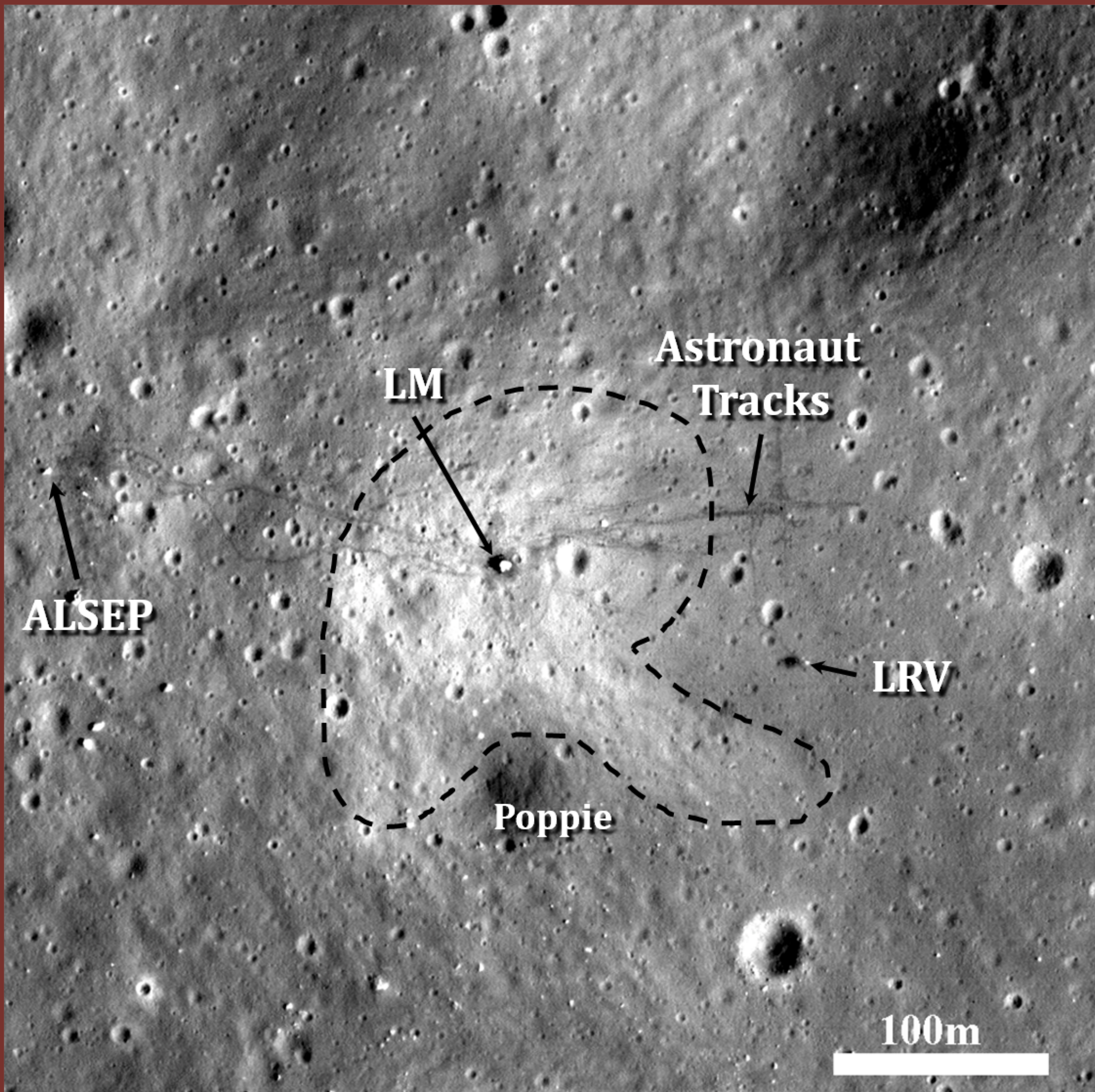
Surveyor 1
Image M122495769L
(*i*=23.3°, *e*=3.7°,
g=26.9°)

Surveyor 5
image M106726943L
(*i*=27.9°, *e*=1.8°,
g=29.7°)

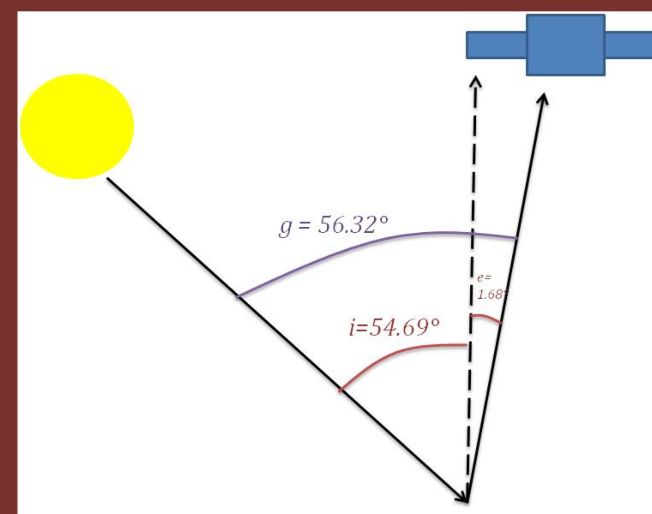
Surveyor 6
image M117501284L
(*i*=81.6°, *e*=1.7°,
g=83.3°)

Surveyor 7
image M175355093L
(*i*=56.2 °, *e*=1.7°,
g=57.6°)

LROC Landing Site Images



Apollo 17 Landing Site
M129086118LE
(*i*=54.69 °, *e*=1.68 °, *g*=56.32 °)



Hypotheses

Hypotheses to explain the increased reflectivity around the Lunar Modules:

1. Redistribution of regolith fines from under the lander to the more reflective zone [*Kreslavsky and Shkuratov*, 2003]

2. Smoothing of the surface by exhaust gas flow [*Kaydash et al.,* 2010]

3. Removal of a more mature surface layer and exposure of less mature soil beneath

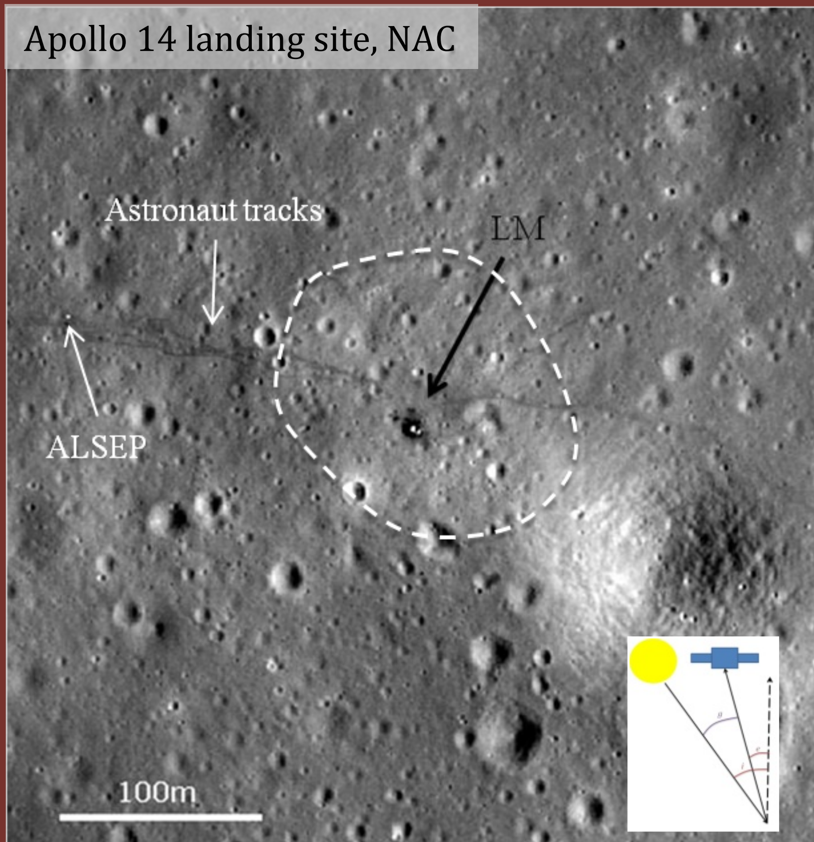
4. Destruction of fine-scale (“fairy-castle”) structure of the regolith [*Hapke and van Horn*, 1963; *Metzger et al*., 2011]

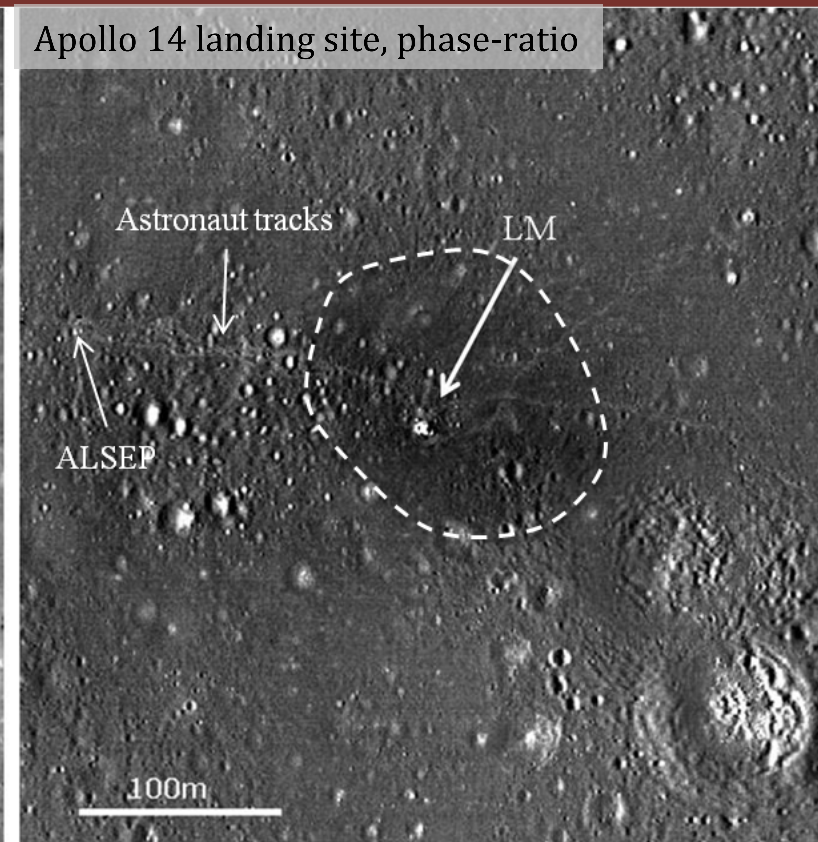
5. Compaction of the regolith

6. Contamination from fuel

7. Combination of these effects

Phase-Ratio Images





NAC image, M11406206L (i=57.86°, e=16.71°, g=41.16°)

$$\frac{\text{M114064206L } i=57.86°, e=16.71°, g=41.16°)}{\text{M114071006L } (i=56.94°, e = 22.23°, g=79.16°)}$$

In particular, the right image is the ratio between a more backward viewing geometry and a more forward viewing geometry. The image shows that the BZ appears darker and is therefore less backscattering.

Measuring the BZ Spatial Extents

- Apollo BZ diameters range from ~130 – 280 m

- Apollo 12 is the largest because the LM hovered near Surveyor Crater during descent, tilting back and forth to avoid moving horizontally

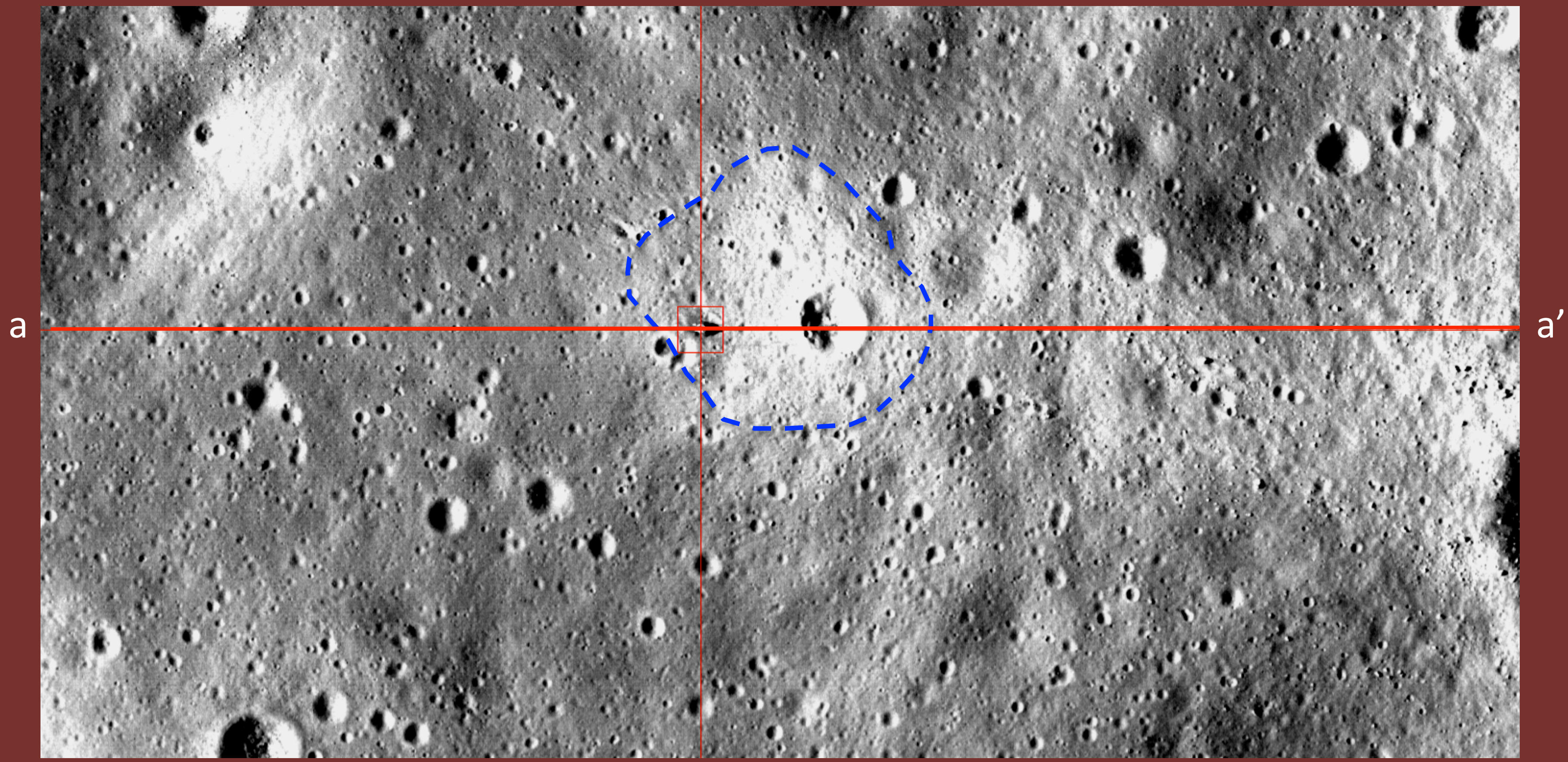
[*Conrad et al.*, 1969; *Harland*, 2008].

- Average Apollo BZ area is over 10 times larger than Luna BZs and over 100 times larger than Surveyor BZs

Mission	E-W diameter (m)	N-S diameter (m)	Elliptical Area (m^2)
Ap11	149	217	25403
Ap12*	279	246	53872
Ap14	134	202	21339
Ap15	142	168	18725
Ap16	216	203	34483
Ap17	132	183	18888
Apollo Average	**175**	**203**	**28785**
Luna Average	**56**	**47**	**2100**
Surveyor Average	**19**	**14**	**215**

*Apollo 12 measurements include Surveyor Crater.

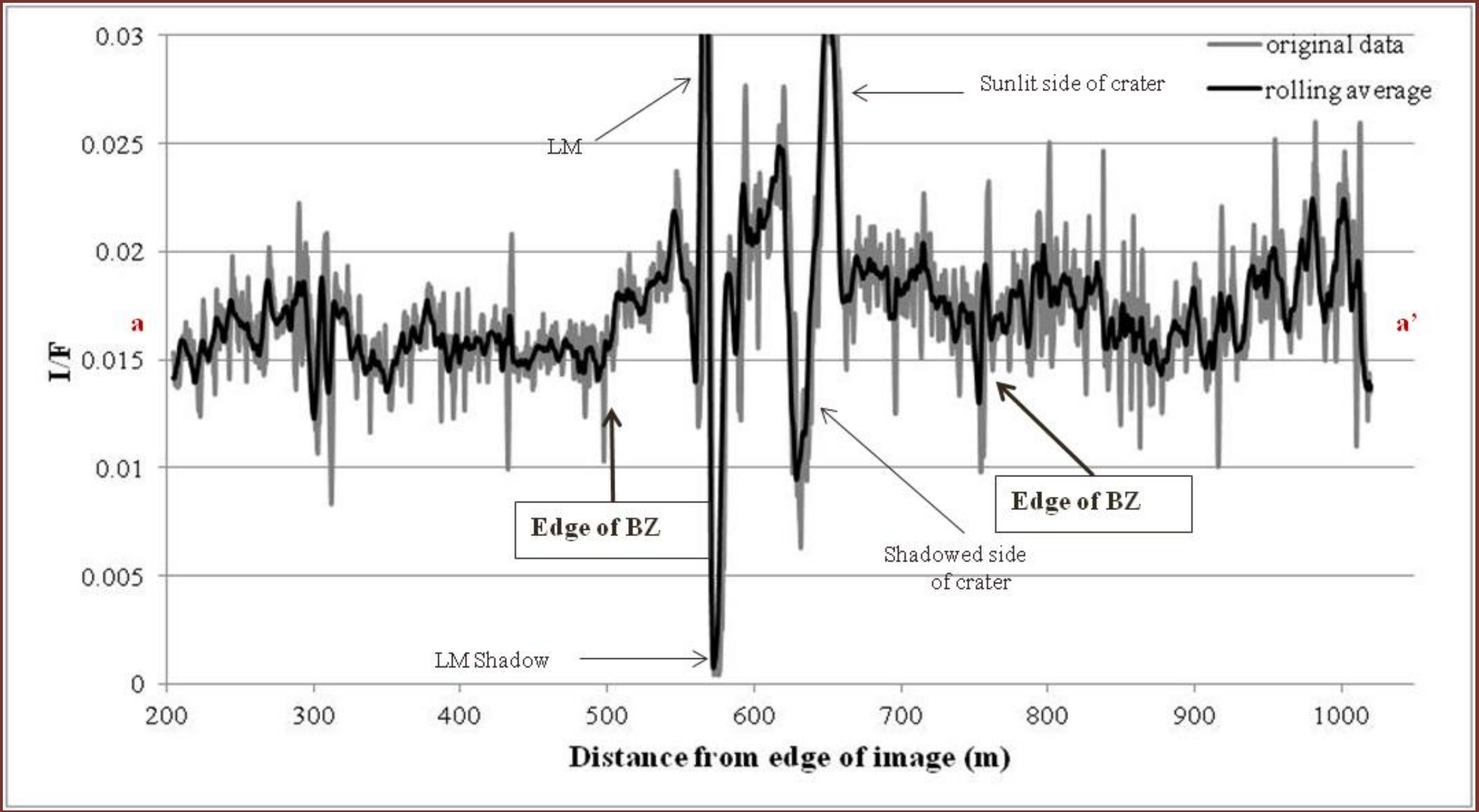
Reflectance Profiles - Apollo



Apollo 11, NAC image M150361817RE

I/F = observed radiance (I)/solar irradiance (F) from normally illuminated Lambertian surface

Reflectance Profiles - Apollo



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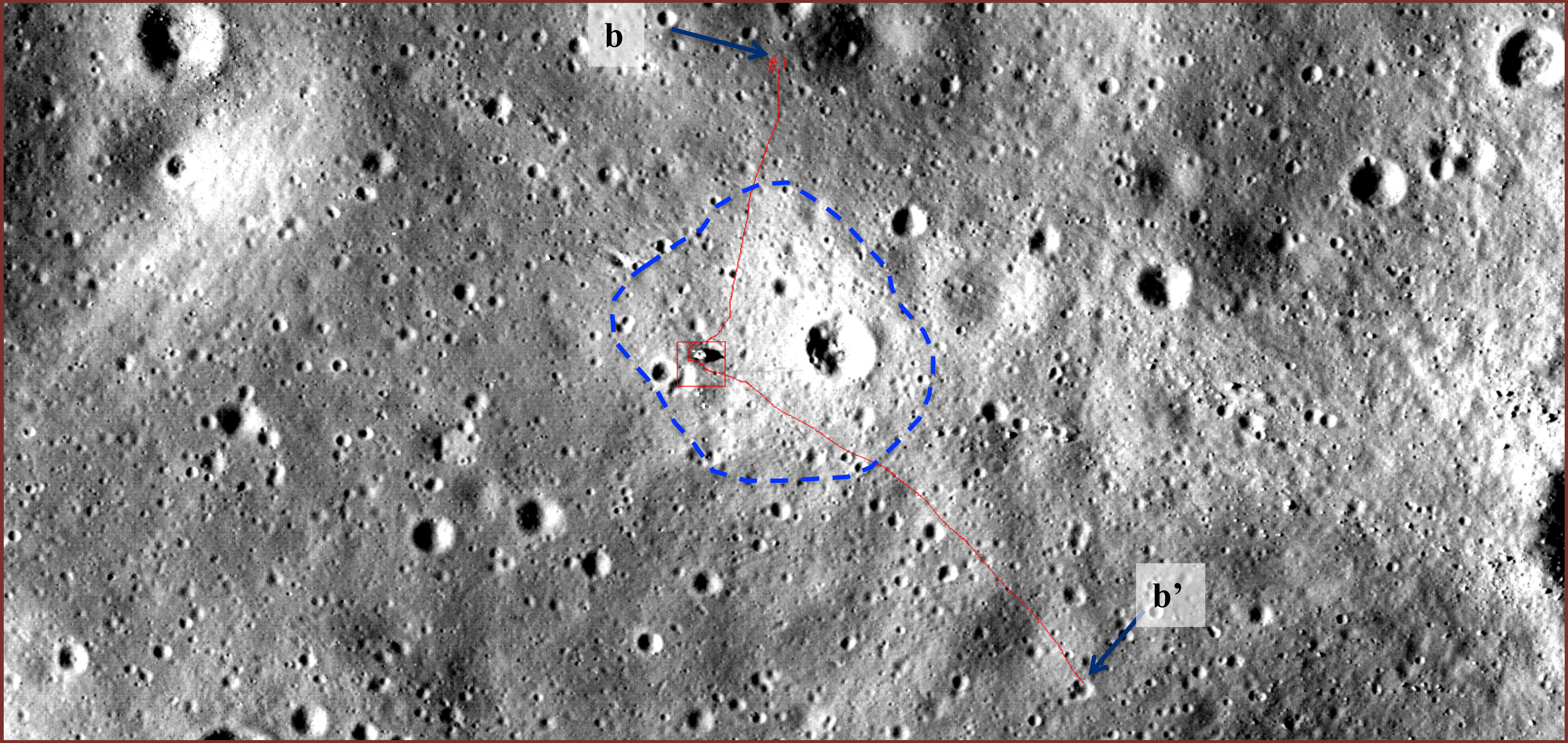

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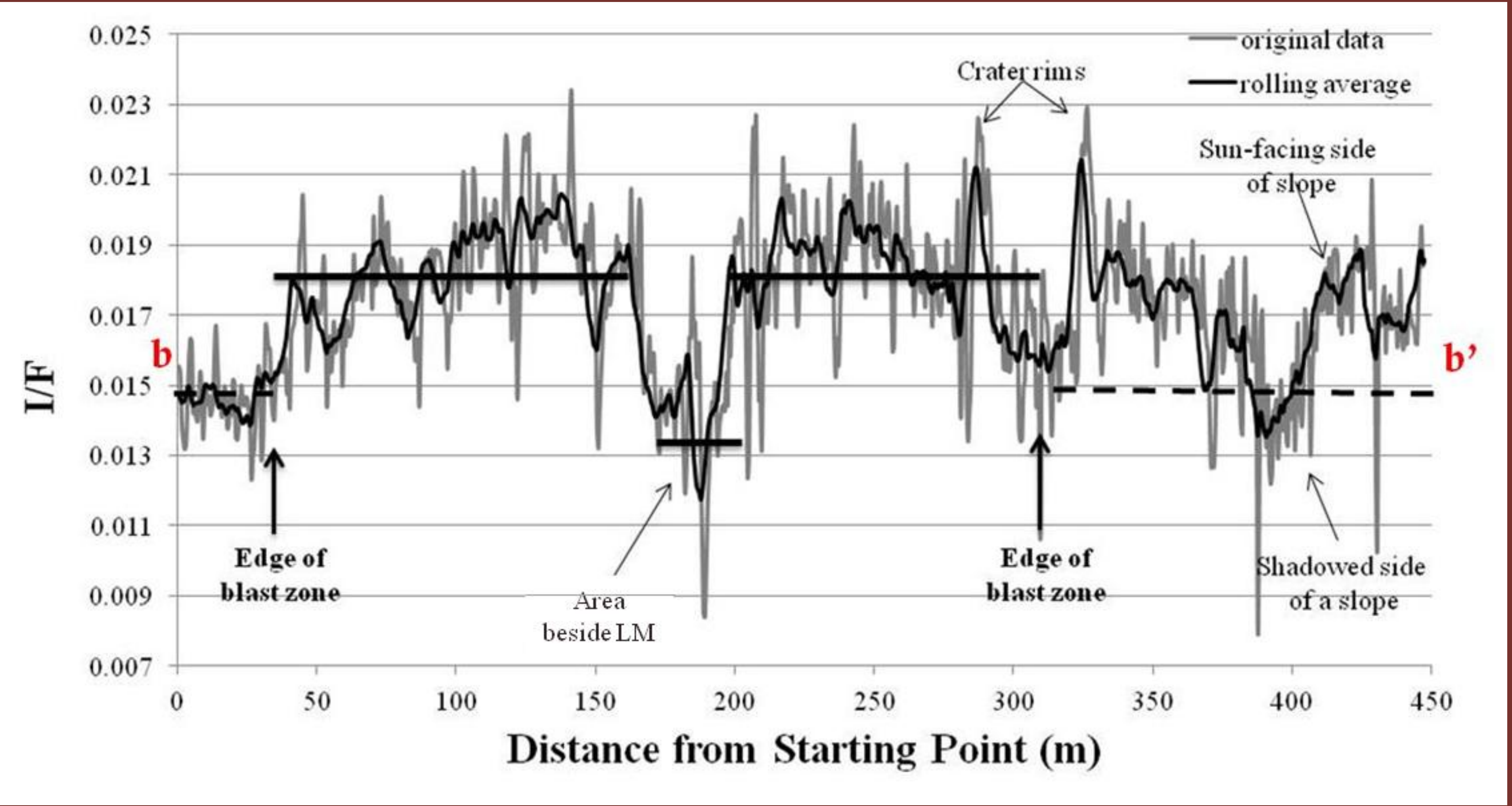

Apollo 11, NAC image M150361817RE

I/F = observed radiance (I)/solar irradiance (F) from normally illuminated Lambertian surface

Photometry Observations

Mission	Average I/F_bz	Average I/F_bckgrd	Average Normalized I/F*
Ap11	0.028	0.027	1.053
Ap12	0.059	0.053	1.125
Ap14	0.063	0.057	1.094
Ap15	0.041	0.036	1.143
Ap16	0.099	0.095	1.044
Ap17	0.032	0.029	1.108
L16	0.041	0.037	1.106
L17	0.038	0.036	1.067
L20	0.076	0.070	1.083
L23	0.046	0.042	1.102
L24	0.038	0.033	1.161
S1	0.039	0.036	1.066
S5	0.044	0.040	1.114
S6	0.040	0.038	1.141
S7	0.070	0.068	1.024

*Normalized I/F = (IoF_bz)/(IoF_background)

Data reported for a phase angle of 30°

Average I/F values are between **2 and 16%** higher within the blast zones than outside

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Apollo:
1.095 ± 0.039
Mass: 15,000 – 16,500 kg

Luna:
1.104 ± 0.036
Mass: 5800 kg

Surveyor:
1.086 ± 0.052
Mass: ~300 kg

Data reported for a phase angle of 30°

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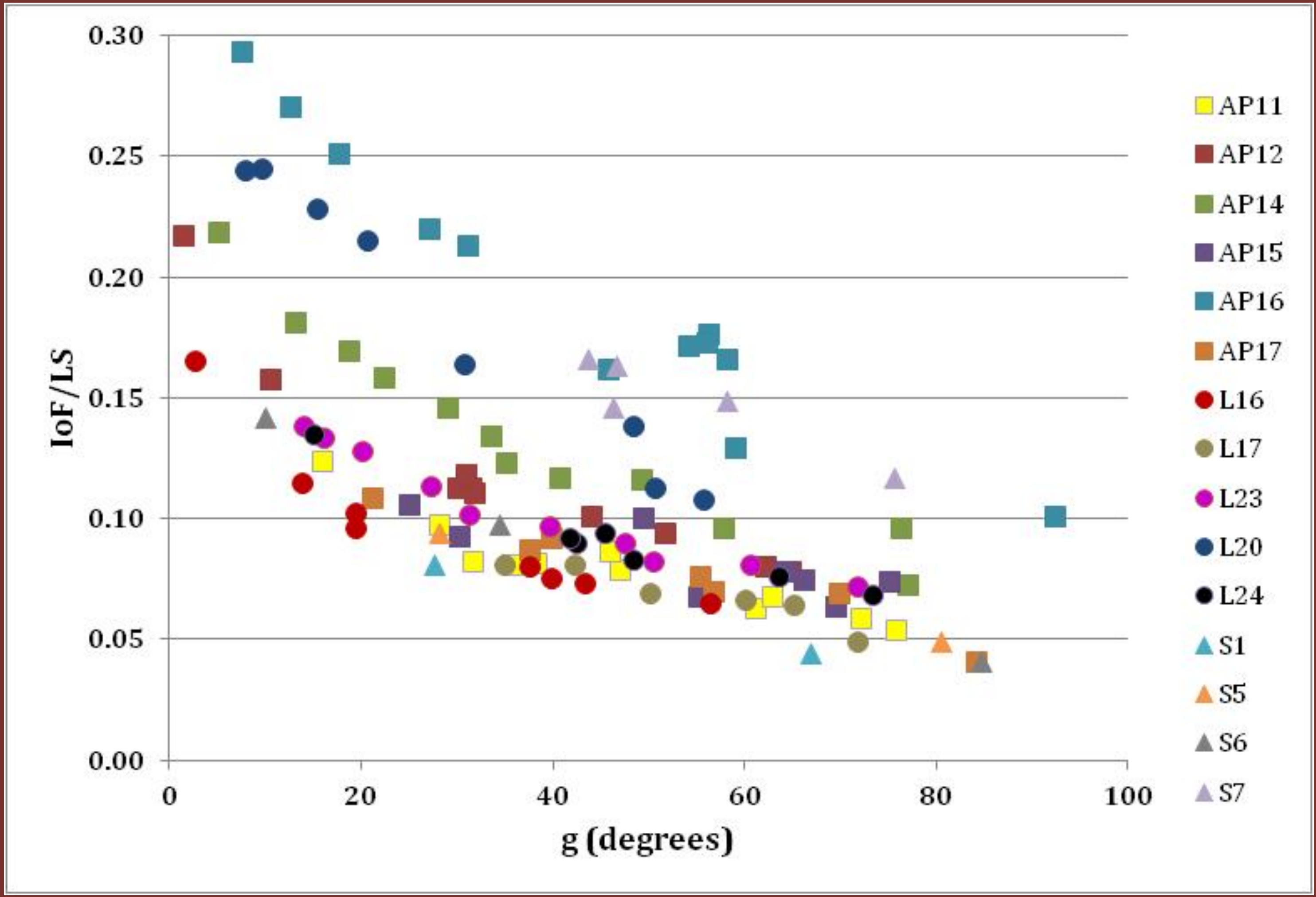
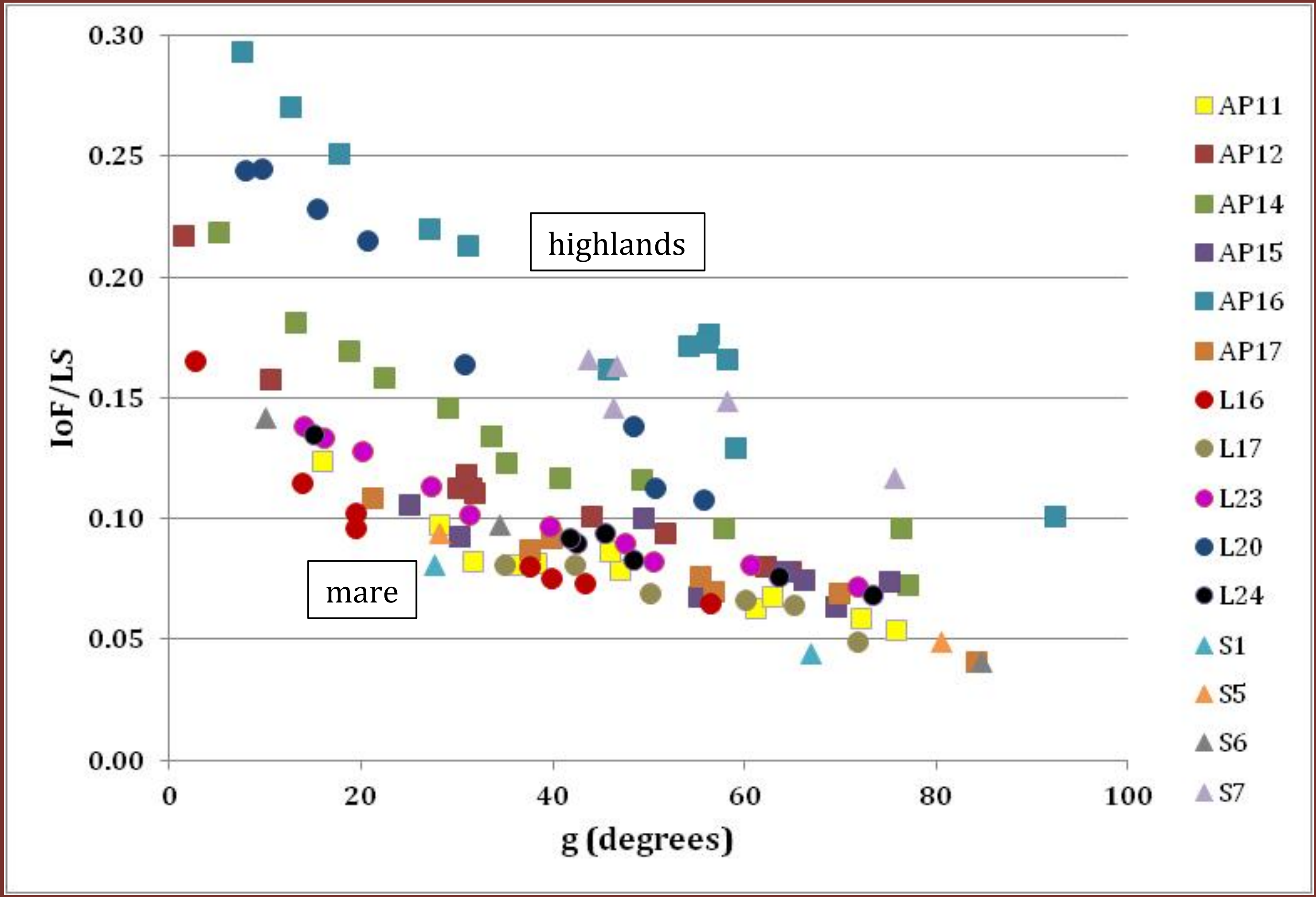


Lommel-Seeliger Function (LS): $LS = \mu_0 / (\mu_0 + \mu)$ $\quad \mu_0 = \cos(i); \mu = \cos(e)$

Photometry Observations



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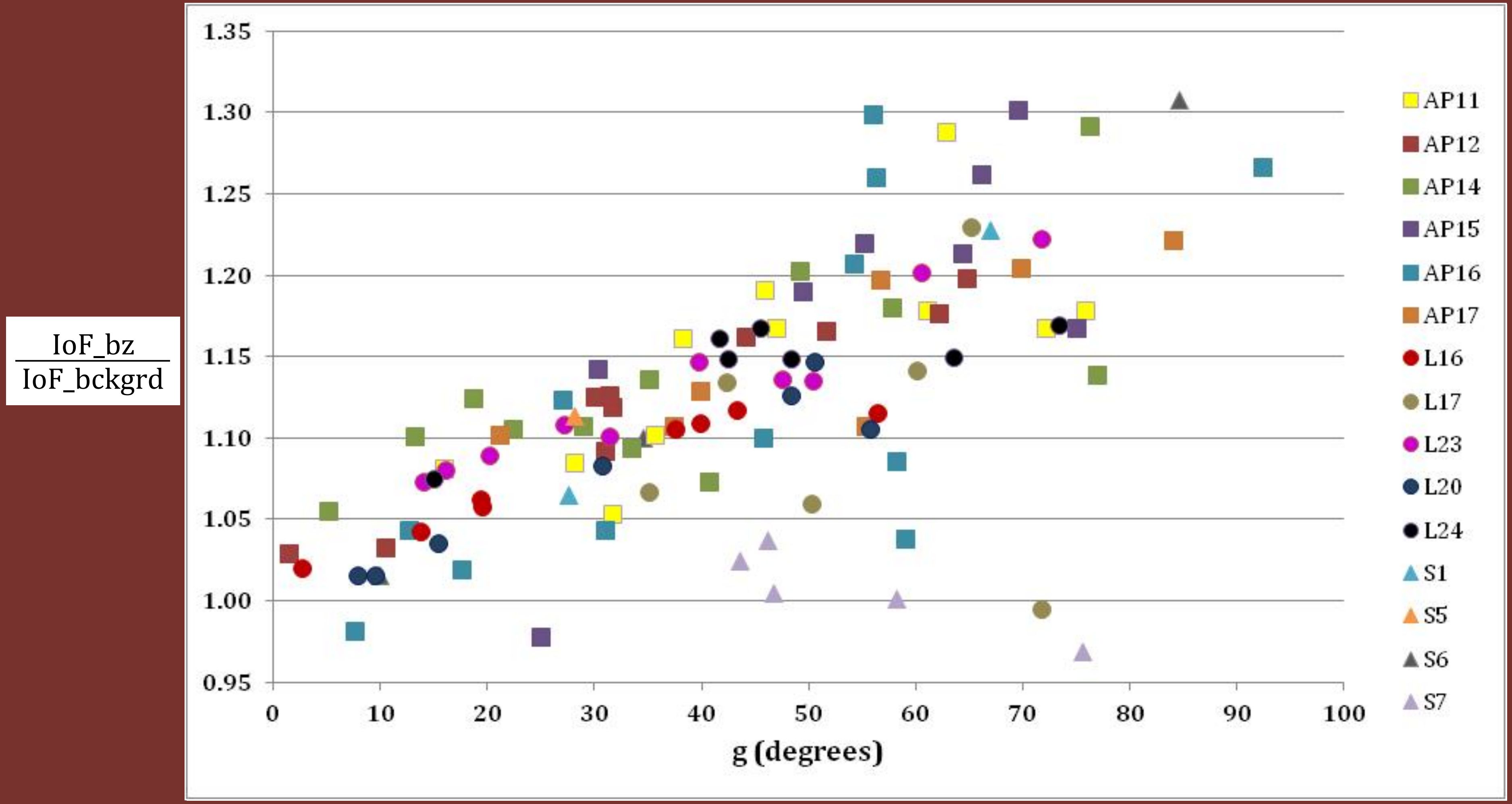
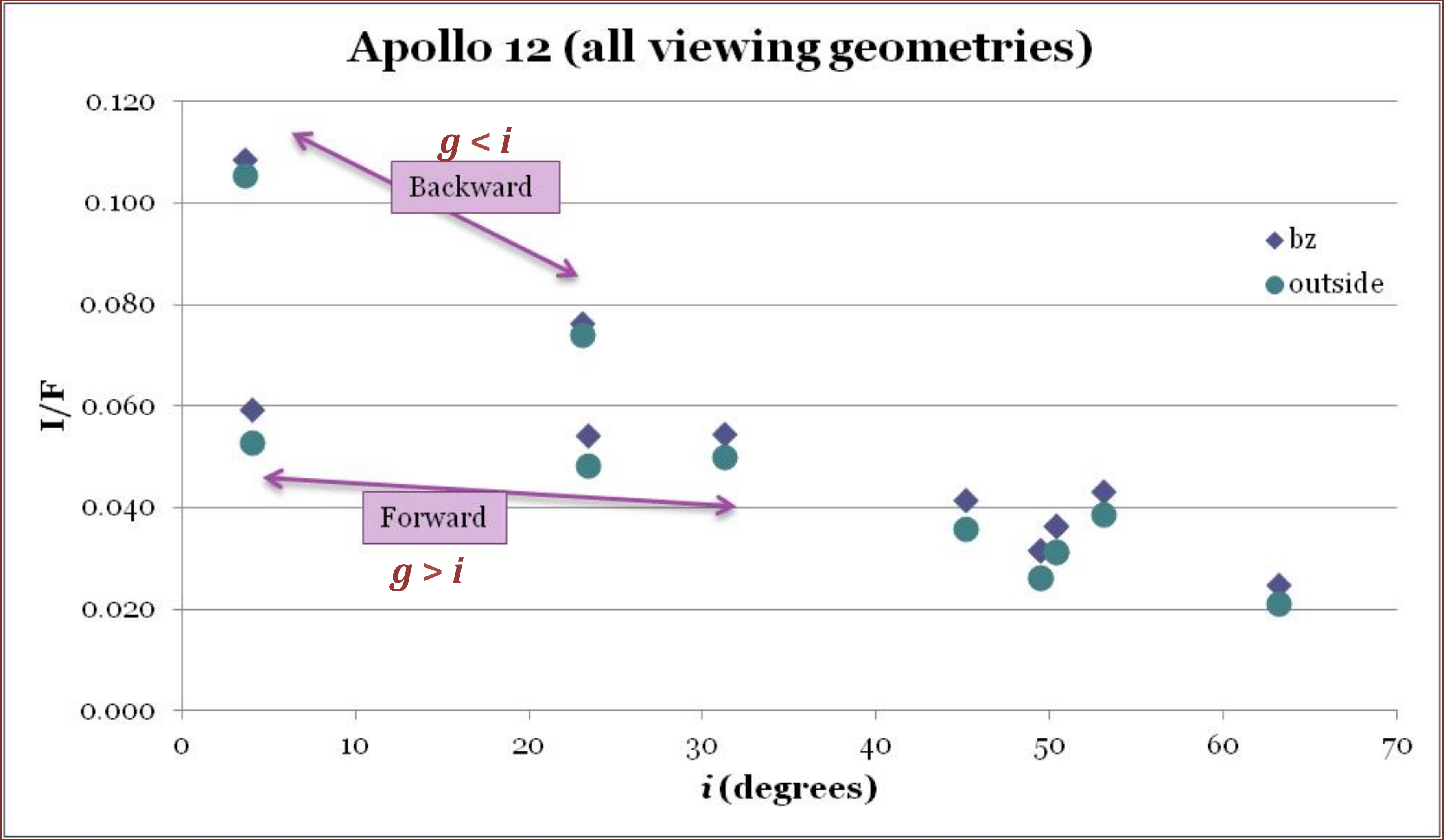
Photometry Observations



Effects of Viewing Geometry



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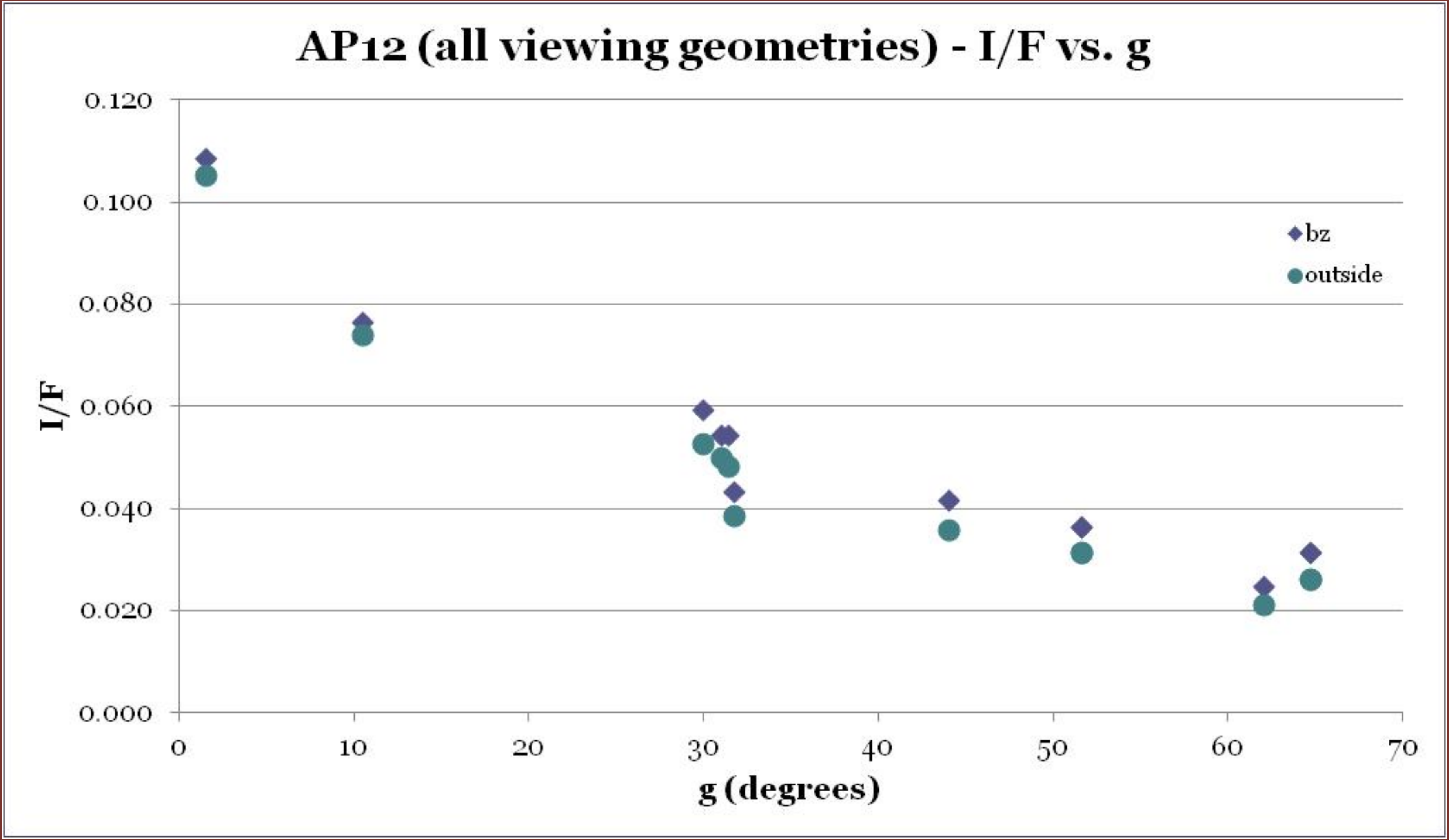

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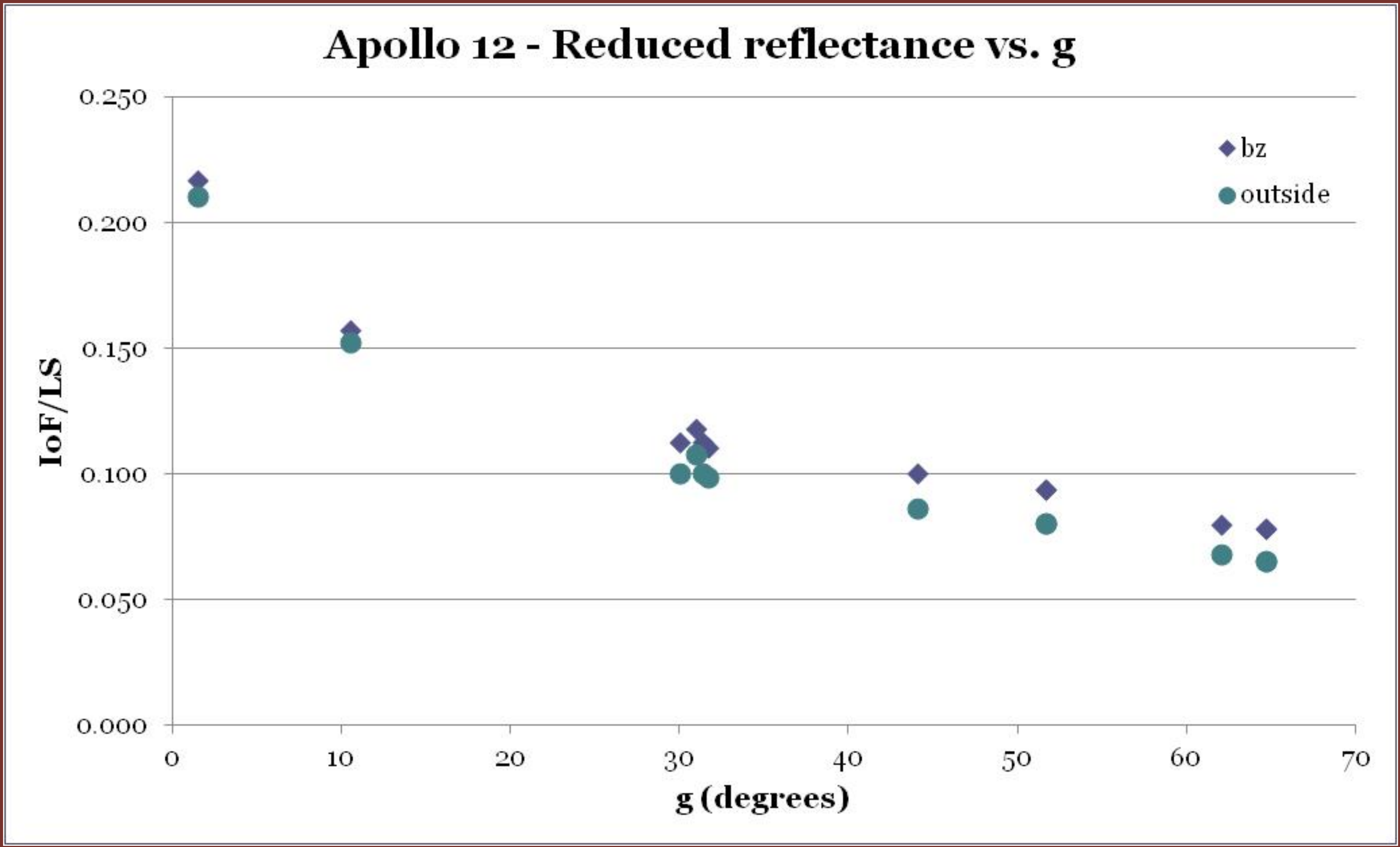


Summary of Key Points

•I/F values are greatest with the BZ annular region

-Separation increases as a function of phase angle (and incidence angle)

-Consistent with increase in forward scattering character in BZ

-Phase-ratio images show that the BZ appears to be more forward scattering (less backscattering) than the undisturbed background regions

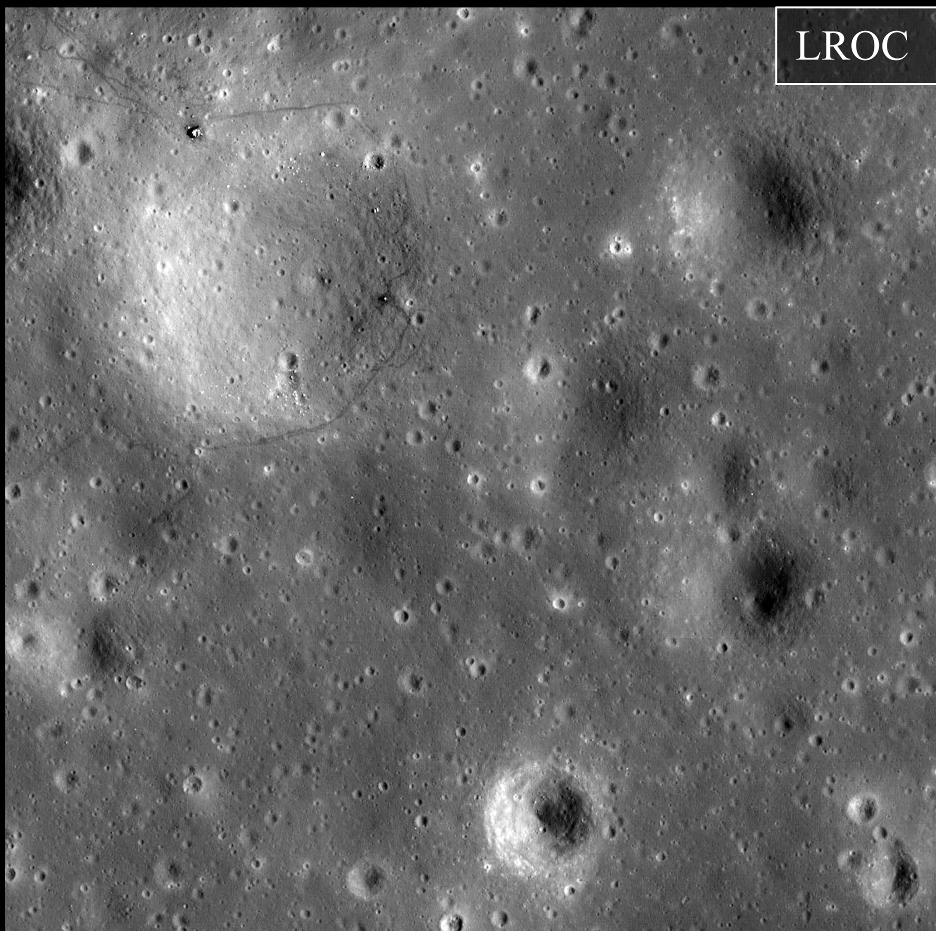
-Separation between BZ and background I/F values increases with increasing incidence angle

-Apollo, Luna, and Surveyor sites have different BZ areas due to differences in lander mass, but reflectance variations are the same (within standard deviations) for all sites

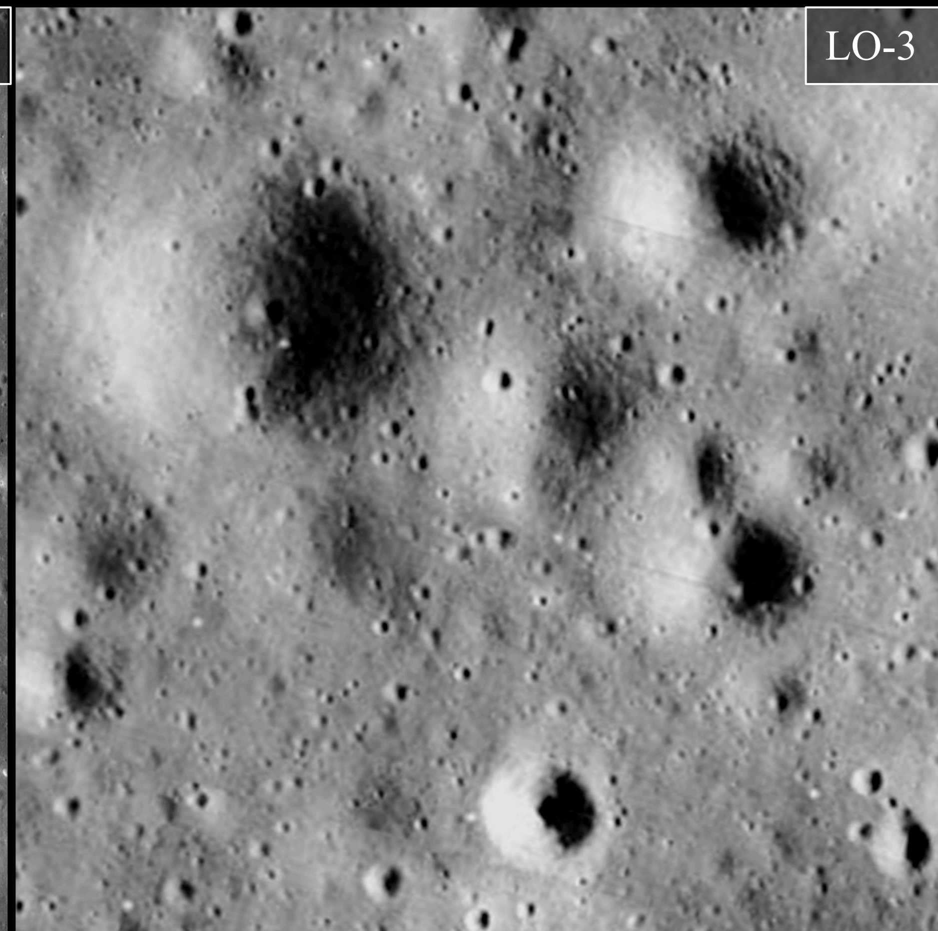
-Destruction of fairy-castle structure (microscopic scale) and/or smoothing of small-scale topography (macroscopic scale) may explain reduction of backscattering characteristics in the blast zones.

BACK UP SLIDES

Motivation

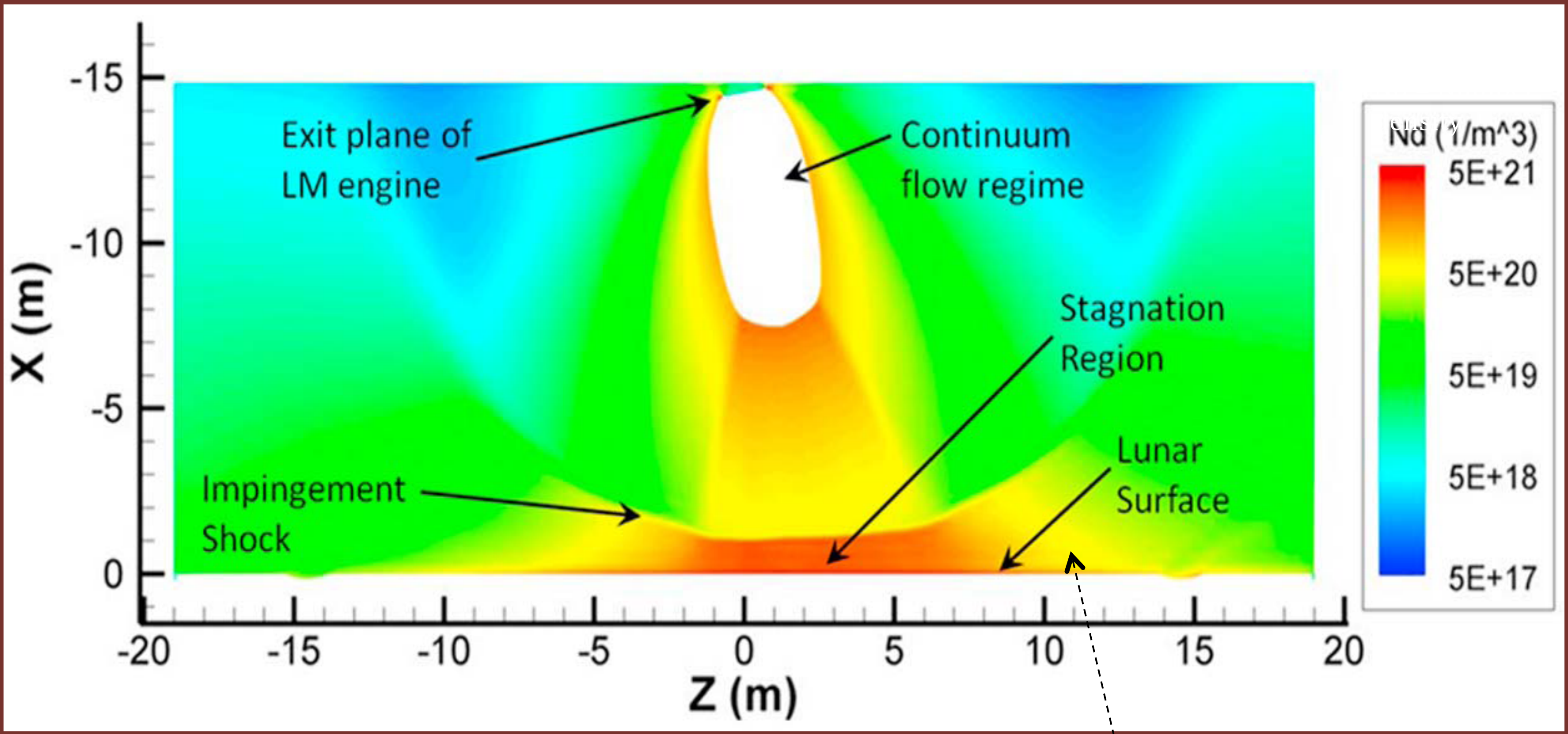


M175428601RE, i = 45°, e = 1°, g = 44°



LO3-154-H3, i = 67°, e = 2°, g = 69°

Characteristics of Rocket Exhaust Plumes



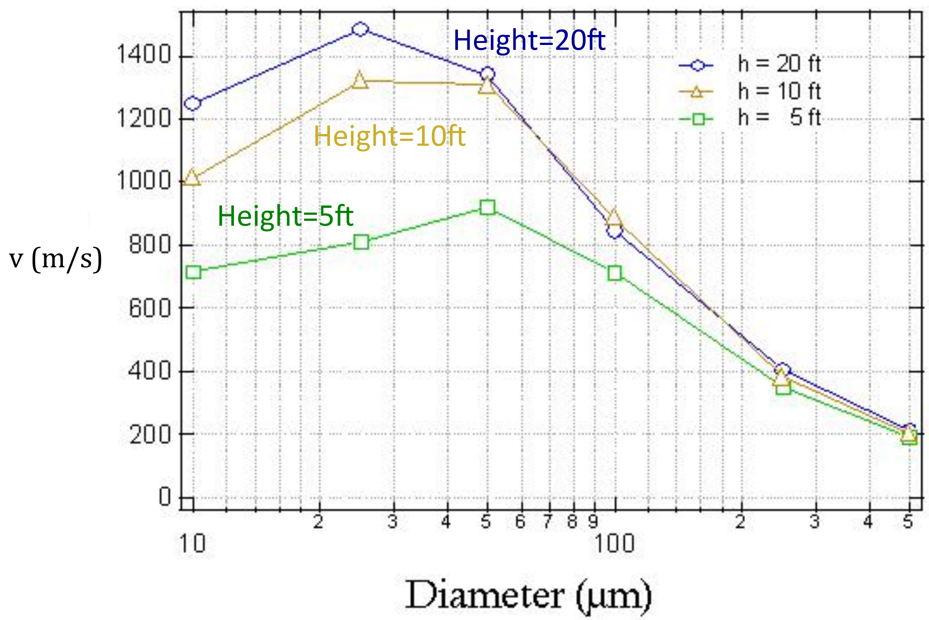
Supersonic, horizontal jet

*CFD and **DSMC simulations by F. Lumpkin and J. Marichalar, 2007

**Computational Fluid Dynamics* ***Direct Simulation Monte Carlo*

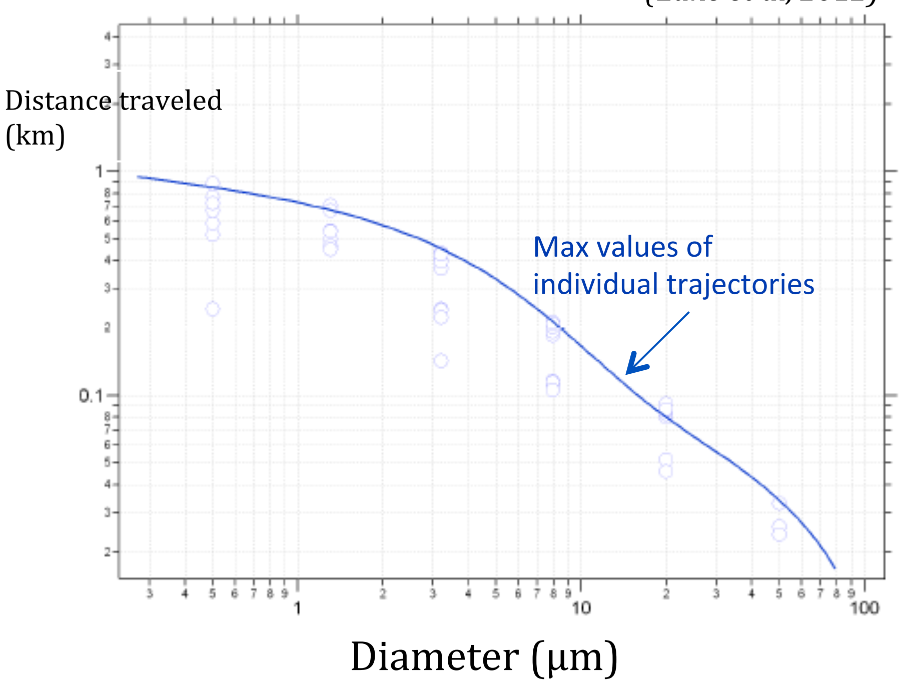
Particle Velocities and Travel Distances

(Lane et al, 2008)



Particle speeds exiting the computational fluid dynamics model boundary.

(Lane et al, 2012)



Radial distance traveled by a particle as a function of particle diameter (for h=45m)

Simulations Indicate…

- Main erosion mechanism is *viscous erosion* – the force of gas on the soil causes grains to roll, hit each other, and "hop" off the surface [*Morris et al.*, 2012].

- Particle-particle collisions within the plume are currently being investigated, but may allow for fine particles to be redistributed close to the lander [*Morris et al.*, 2012].
  - Up to 20% of particles may be engaged in collisions [*Berger*, ASCE Earth and Space 2012 presentation]
  - Creates a diffuse dust spray
  - Get scattering outside of dust sheet

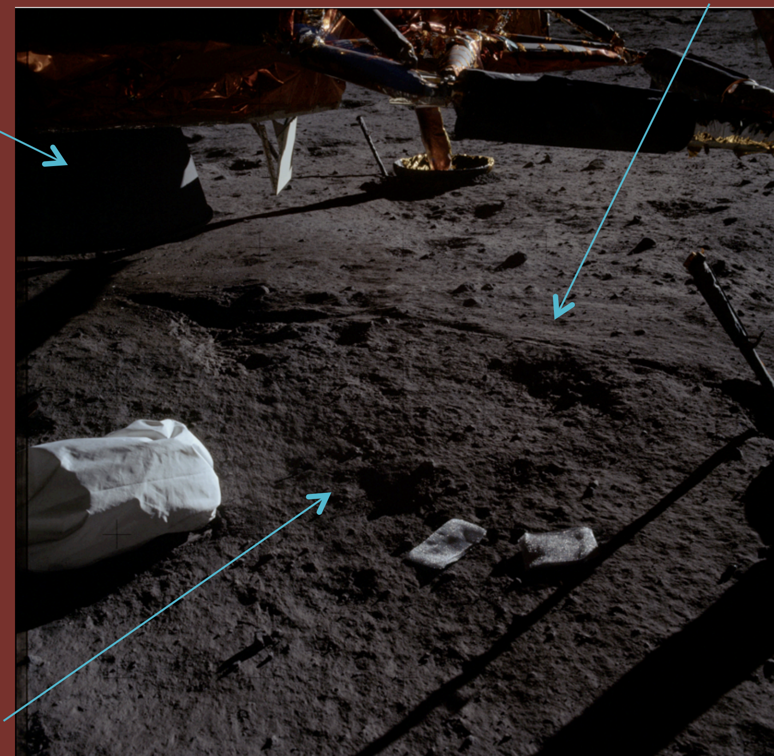
- Dynamic pressure would probably not be enough to compact the surface because the static pressure is very small at only a meter or two away from the rocket nozzle [*Metzger et al.*, 2011].

Surface Photographs seem to show Regolith Brightening

Buzz Aldrin, footpad, and disturbed area, including possible exhaust brightening right to left, behind Aldrin [NASA]

Smoothed?

Nozzle



Roughed up, eroded area

Disturbed region beneath the LM

Apollo Soil Sample Data

Soil Samples

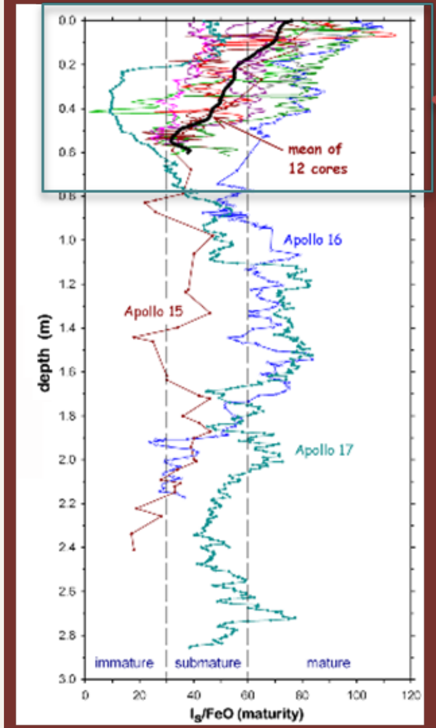
Inside BZ

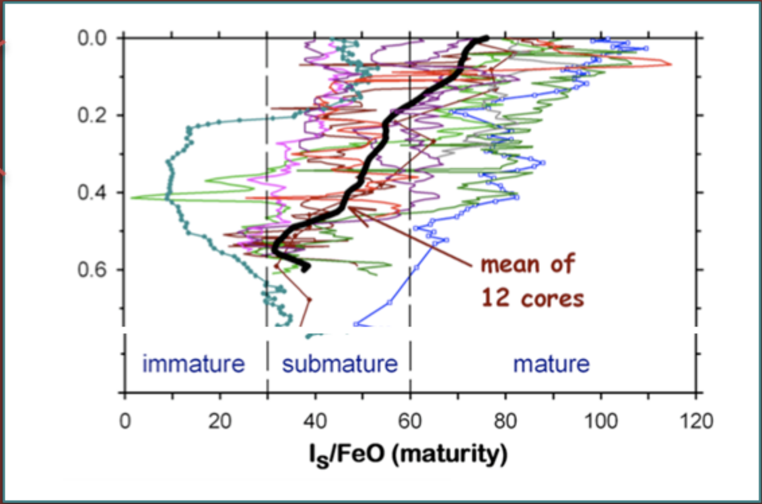
Average grain size:
49.3±13.4 μm
Average I_S/FeO:
62.4±16.3

Outside BZ

Average grain size:
49.7±13.8 μm
Average I_S/FeO:
62.5±16.6

Core Samples

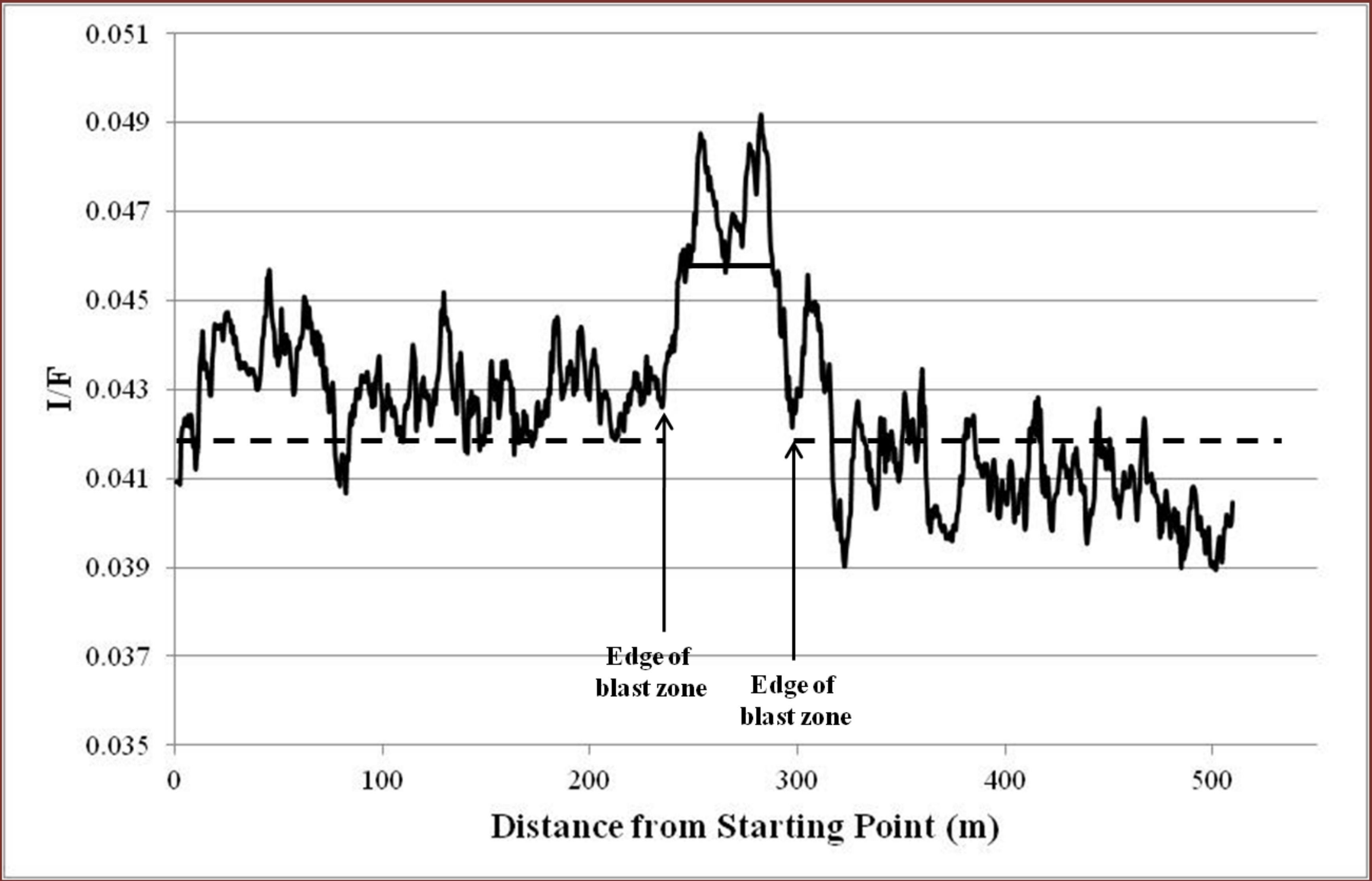




Variation in regolith maturity with depth in Apollo regolith cores *(New Views of the Moon, 2006)*

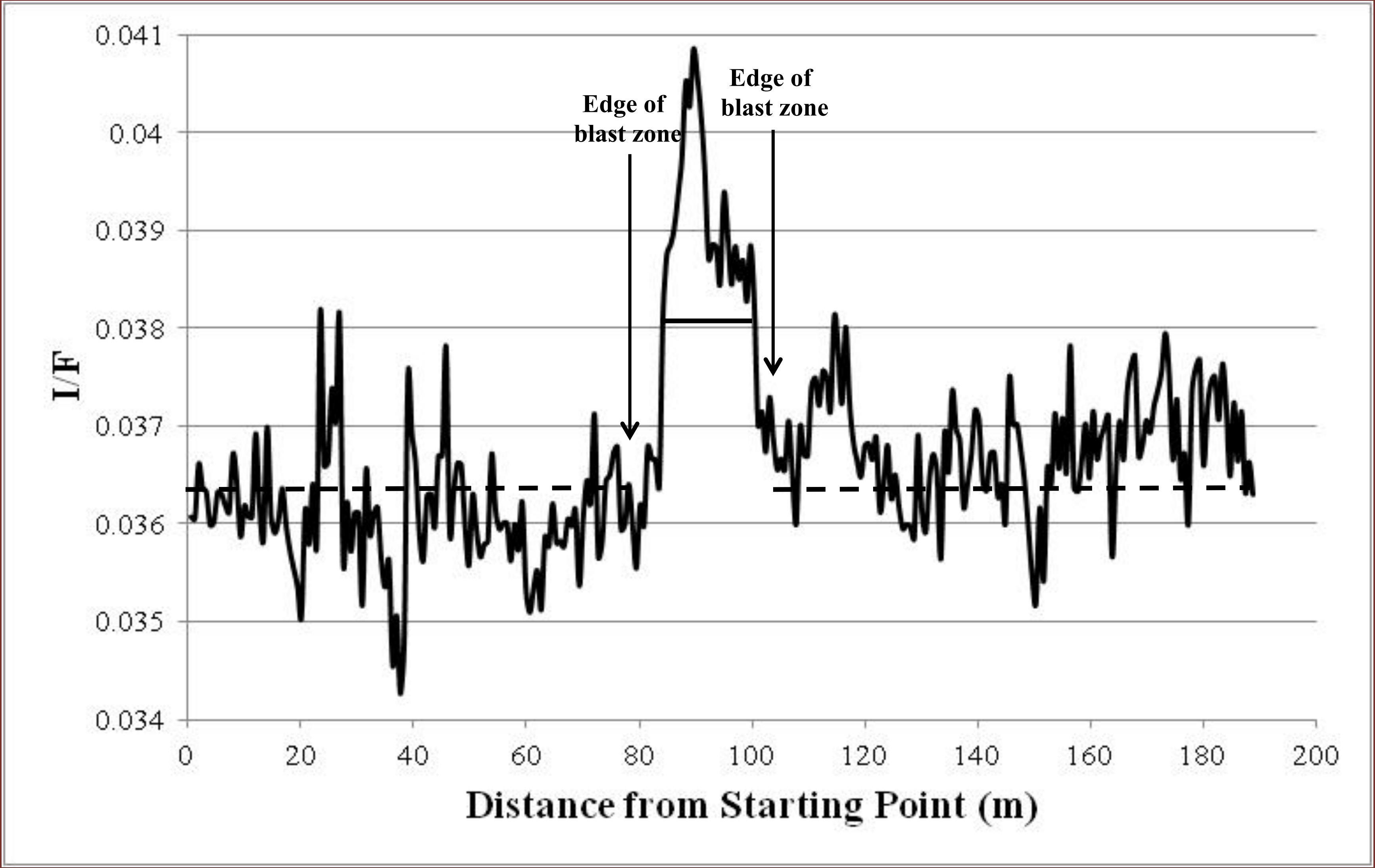
Maturity typically does not change significantly within first 20cm of regolith

Reflectance Profiles - Luna



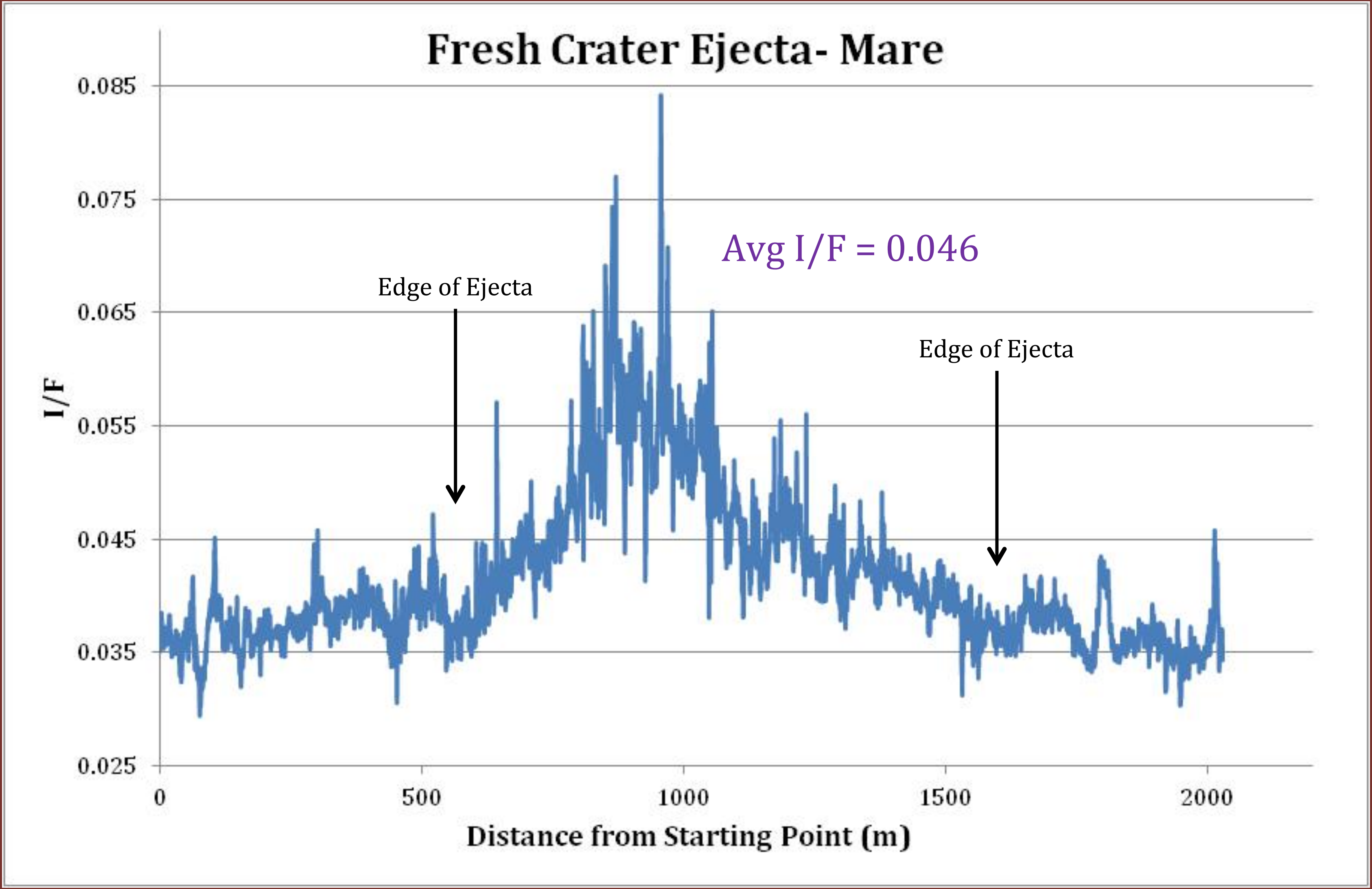
Luna 23, NAC image M106468527R

Reflectance Profiles - Surveyor

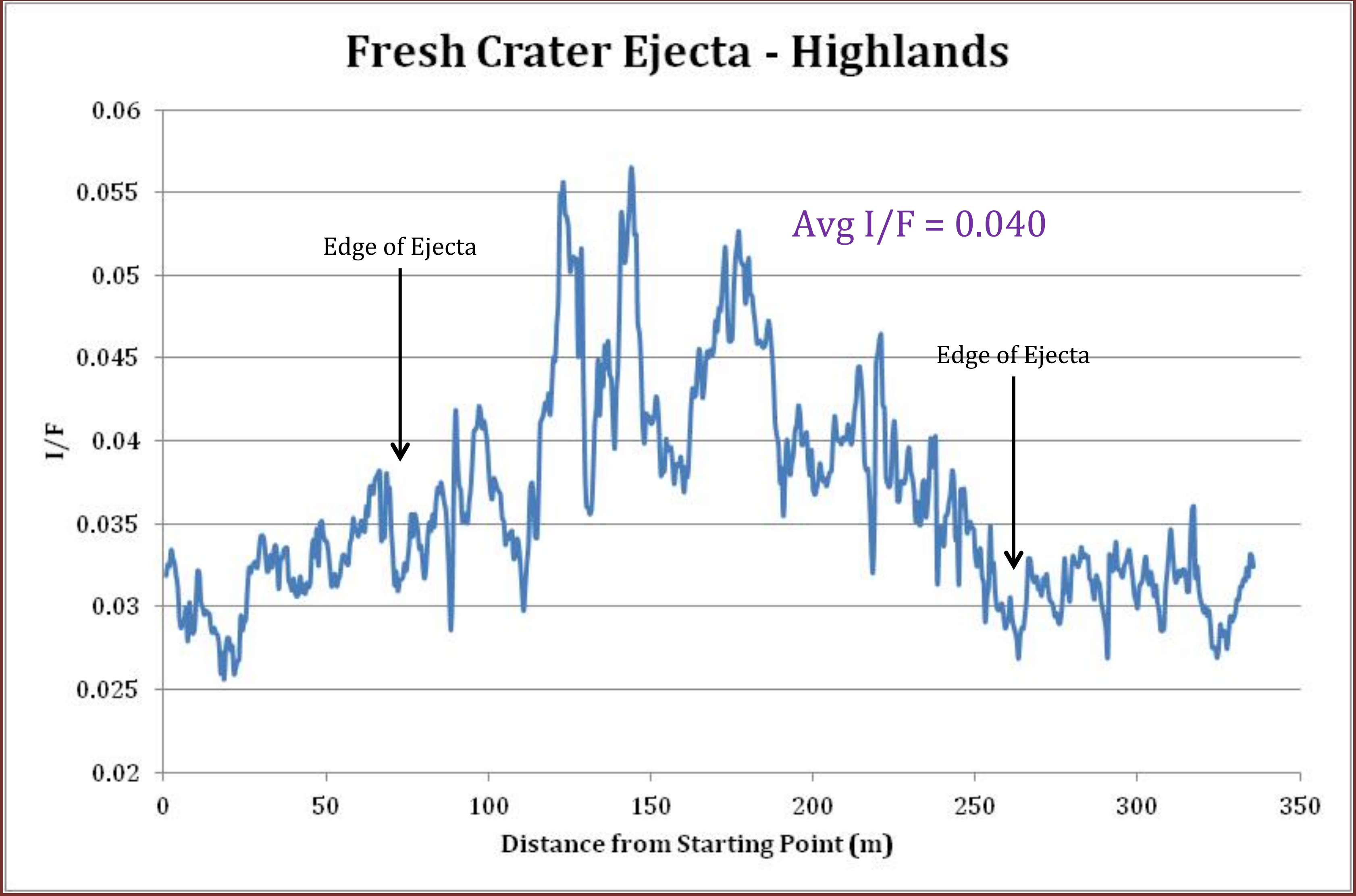


Surveyor 1, NAC image M122495769LE

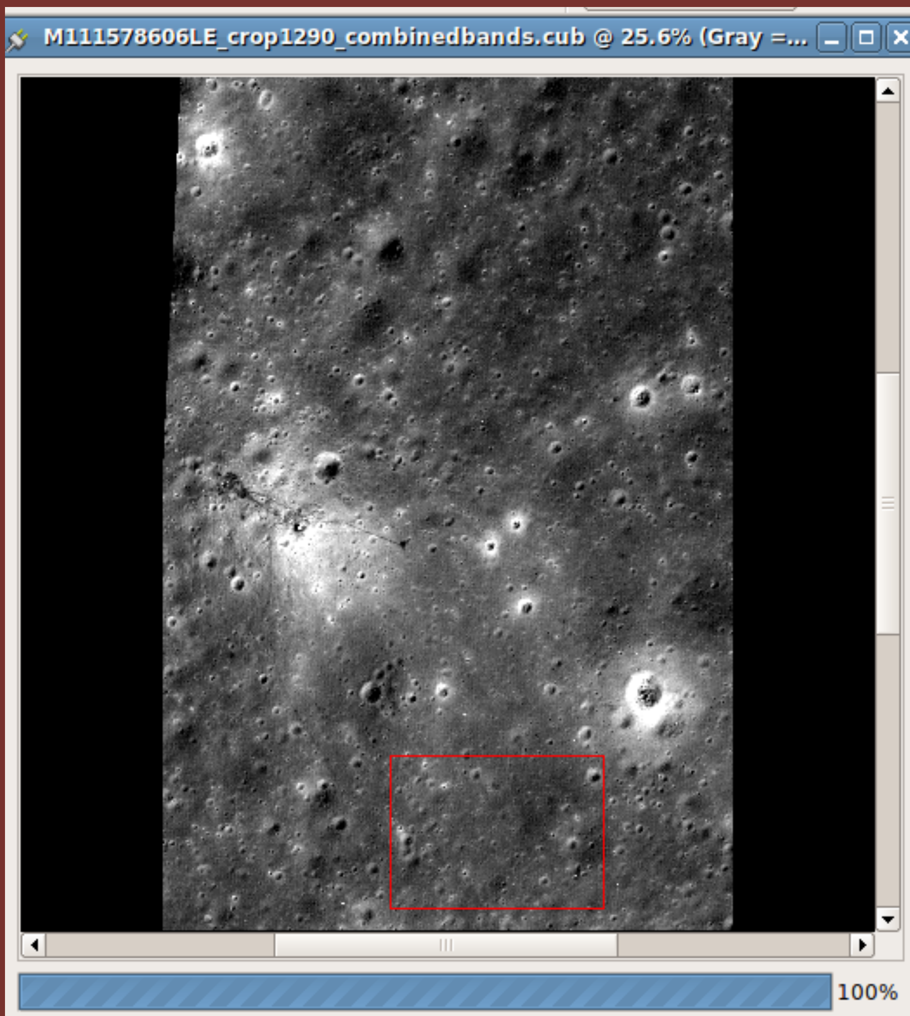
Fresh Craters

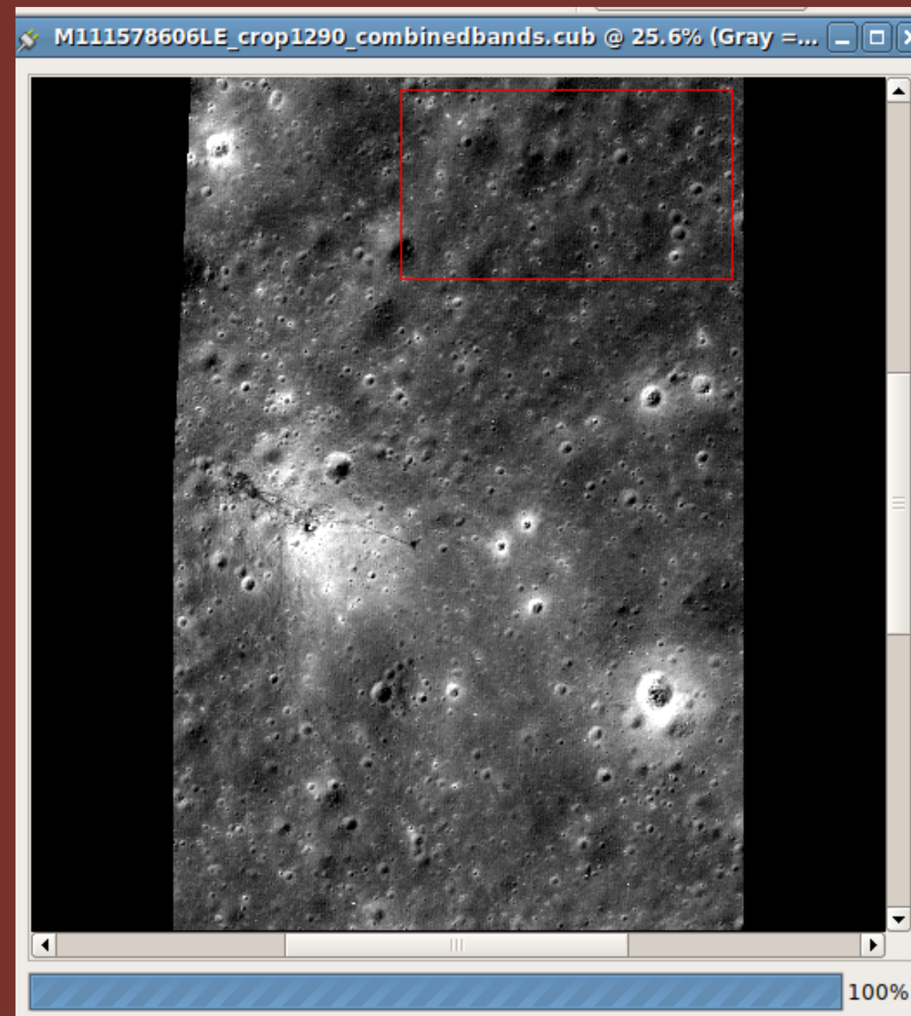


Fresh Craters



Determining Background I/F Values

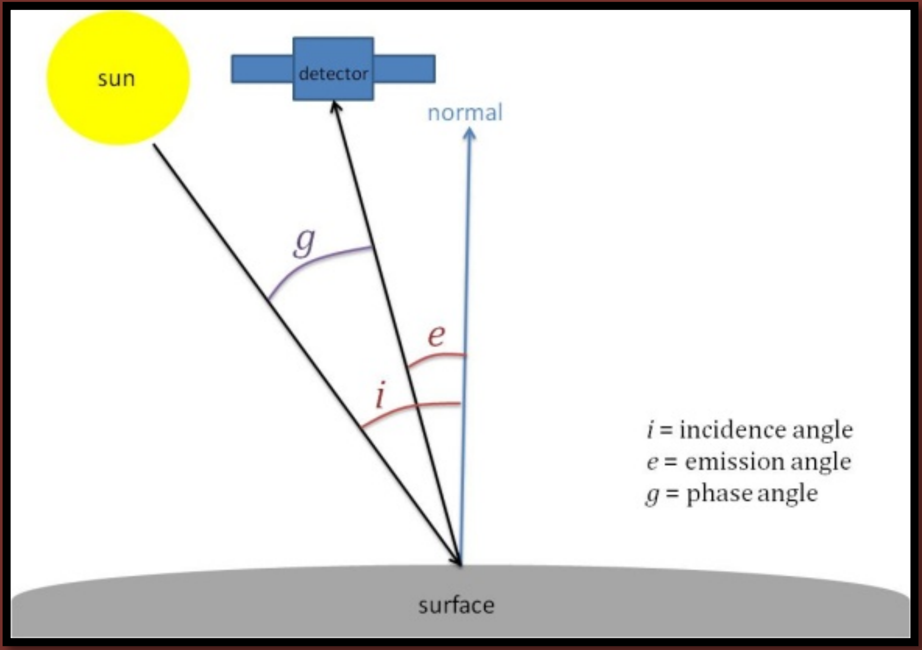




Apollo 15, NAC image M111578606LE
i = 37.9°, *e* = 22.3°, *g* = 56.2°

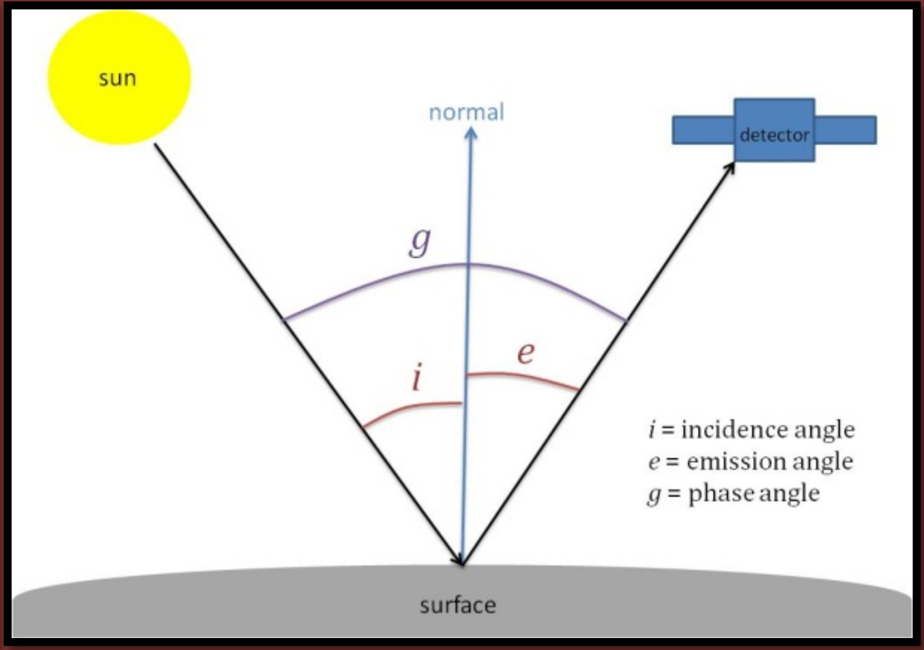
Viewing Geometries

Backscattering Geometry



$g < i$

Forward Scattering Geometry



$g > i$

Conclusions

Hypothesis	Test				
	Exhaust Plume Modeling	Core Sample Characteristics	Soil Data (grain size, I_S/FeO)	Surface Photography	Photometric Analysis*
Surface Smoothing	✓	—	—	✓	✓
Redistribution of Fines	✘	—	—	—	✘
Compaction	✘	—	—	—	✘
Exposure of less mature soil	—	✘	✘	✘	✘
Destruction of small-scale structure	✓	—	—	✓	✓

—= Not applicable or Indeterminate
*More conclusive modeling is planned for future work